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Jason Mossman (Spiral Technology) and David R. Perkins, "Rocket Propulsion Technology Impact on
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The High Frontier Conference XV
(Princeton, NJ, 7-9 May 2001) (Deadline 01 May 2001)

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PHILIP A. KESSEL
Technical Advisor
Space and Missile Propulsion Division

Date

ROCKET PROPULSION TECHNOLOGY IMPACT ON TSTO LAUNCH SYSTEM COST

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DISTRIBUTION STATEMENT A

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Abstract

The benefits of advanced liquid rocket propulsion technology are evaluated for two-stage-to-orbit (TSTO) reusable launch systems. Life cycle cost (LCC) is used as a figure-of-merit and is driven by high launch rate requirements. This paper reports the methods and results of that study. The reported analysis focused on chemical rocket propulsion using either hydrogen or hydrocarbon fuels, and oxygen or high purity hydrogen peroxide as oxidizers. Results indicate that advanced rocket propulsion can cut life cycle costs in half and recurring costs (cost for additional flights) by a factor of three. The most important propulsion parameter to be improved for this class of vehicle is the reusability of the rocket engines, with performance improvements a distant second. Additionally, a TSTO vehicle using liquid oxygen and hydrocarbon propellants in both stages has the lowest LCC. Results were relatively insensitive to engine reliability and cost.

Introduction

The expense of space access is the single greatest barrier to development and exploitation of space. Based on recent publications, current launch costs per pound to low-earth-orbit (LEO) range from \$1530 for a Russian Proton K launch, to \$3870 for an Atlas 2A, to \$3000 for Delta IV M+(5,4), to even \$10,300 for Shuttle or almost \$15,000 for Pegasus XL.¹ Past studies have concluded that reusable launch systems with good operability features can substantially lower that cost. The most simplistic vehicle concept considered over time has been the single-stage-to-orbit (SSTO) concept, which, unfortunately, is extremely stressing to both propulsion performance and allowable SSTO inert weights. The expense of even marginal progress toward enabling SSTO vehicles (e.g. the NASP, X-33 and X-34 programs) highlights that SSTO vehicles are still very risky developments. Study of more pragmatic near-term launch vehicle configurations is needed. Without new launch vehicle development in the near future,

launch costs will remain at values of \$2000 to \$10,000 per pound to LEO.

One vehicle type of interest is the fully reusable TSTO launch vehicle.² Such a design greatly reduces the sensitivity of the vehicle design to performance, weight, and mission. This paper focuses on an LCC comparison of five different rocket powered TSTO launch vehicle concepts (see Fig. 1). The first stage, referred to as the Booster, considered both hydrocarbon and hydrogen fuels. The second stage, called the Orbiter, considered hydrogen and hydrocarbon fuels as well as a peroxide/JP propellant combination. The five vehicle concepts are listed in Table I.

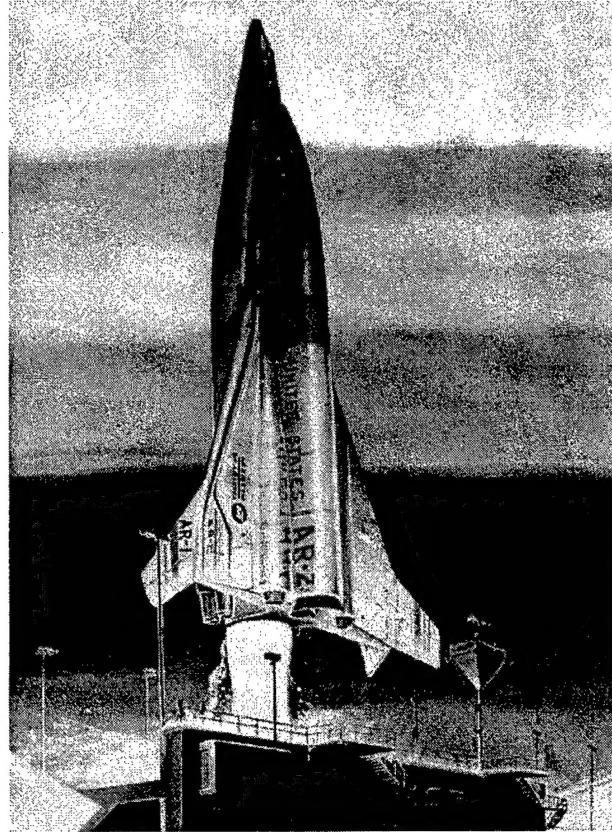


Fig. 1 Notional TSTO Vehicle

Table I. Vehicle concept propellant combinations

| Concept | Booster | Orbiter |
|---------|---------------------|-----------------------------------|
| 1 | LOX/HC | H ₂ O ₂ /JP |
| 2 | LOX/HC | LOX/LH ₂ |
| 3 | LOX/LH ₂ | H ₂ O ₂ /JP |
| 4 | LOX/LH ₂ | LOX/LH ₂ |
| 5 | LOX/HC | LOX/HC |

Three advanced propulsion technology levels and a zero technology baseline were evaluated for each of the five vehicle concepts. The vehicles were projected against an operations model to derive a life cycle cost. Cost elements included development, production, facilities, operations and costs associated with catastrophic failures. For this study, vehicles were sized to deliver a 12,000-pound payload to a polar inclination low earth orbit. All vehicle concepts were required to meet the same tempo driven mission model, using the same operations model, and were scaled with common weight and cost estimating relationships.

The assumed mission model was aggressive. Over a million pounds a year are placed into orbit. This gives a best return on any reusable launch system investment. A fast operations tempo was demanded of this system and drove the number of orbiters and boosters and the extent of facilities necessary to achieve the mission model. Payloads were assumed to have very simple vehicle interfaces, and were assumed capable of rapid integration with the vehicle.

A simple operations model was developed that was used to compare the vehicle concepts. It provided facility-processing characteristics that determined both the number of vehicle elements and the scope of required facilities to meet the mission model.

Life cycle cost estimation evaluated development cost, facility costs, production, operations, and unreliability costs.^{3,4} The LCC model was developed to primarily address propulsion technology cost leverage, and is more accurate for cost differences between concepts than for absolute system LCC costs.

Results show a strong advantage of all hydrocarbon-fueled vehicles if advanced rocket technology is pursued. Hydrocarbon stages are inherently smaller and have less inert weight compared to hydrogen-fueled stages. They are also inherently more operable. The analysis also suggests that relatively low recurring costs are feasible with these vehicles if advanced propulsion technology is used.

Rocket Technology and Its Advances

Several parameters have proven to be very important in determining the effectiveness of any particular rocket design. These parameters are derived from the fundamental kinematics of accelerating rockets. The total acceleration that a rocket can perform is referred to as its velocity change (ΔV) and is directly proportional to the specific impulse (I_{sp}) of the rocket. ΔV is directly related to mission capability. For example, the ΔV required to achieve a polar low earth orbit is about 30,000 feet per second.

I_{sp} is a measure of rocket fuel consumption efficiency, and is equal to rocket thrust divided by the total mass flow rate of rocket propellants. Generally, the higher the I_{sp} , the better the rocket performs.

Rocket ΔV is also proportional to the natural logarithm of the ratio of initial to final weight. The higher the weight ratio is, the greater the ΔV . The final weight, which includes any residual propellants, vehicle hardware, and the payload, is driven to comparatively low values when the required ΔV is high. Generally, low inert weight (e.g., high engine thrust-to-weight ratio) is desired.

Now, from a gas dynamics perspective, the I_{sp} is proportional to the square root of the ratio of combustion temperature divided by the mean molecular weight of the exhaust species. High temperature is often achieved through the chemical combustion of a fuel and oxidizer. Molecular weight can be kept low by the choice of those propellants. Liquid hydrogen (LH₂) and liquid oxygen (LOX) combust at a very high temperature (~6500 degrees R) and a very low mean molecular weight of the exhaust species. Rockets using LOX/LH₂ have among the highest I_{sp} of all chemical rockets.

However, there are serious inert weight issues in using LH₂. It has a very low density (about 4 pounds per cubic foot vs. kerosene at 45 pounds per cubic foot). Thus LH₂ tanks are comparatively very large. LH₂ must be stored at very low temperatures (40 degrees R) and therefore requires thick insulation over the tank's entire surface area. Furthermore, since LH₂ is very compressible, it requires very large and powerful turbo-pumps to raise its pressure to 400 atmospheres or more. LH₂-fueled engines have lower thrust-to-weight than hydrocarbon-fueled engines. Lastly, LH₂ density is very sensitive to temperature, so it is very difficult to know precisely how much LH₂ is loaded into a very large volume with any temperature stagnation. Thus, LH₂ tanks require several times more propellant reserves than, say, kerosene. Therefore, the higher I_{sp} of LH₂-fueled rockets does not necessarily mean the lowest weight rocket system, and also causes slower vehicle processing.

Besides the obvious desire to limit engine production cost, other engine characteristics also drive total launch system life cycle cost. Greater engine life reduces the frequency of engine overhaul, and also decreases the number of engines purchased. Lower rocket engine failure rates lead to fewer lost missions, fewer lost vehicles, and less lifetime collateral damage (e.g. damaged facilities). It is possible, through redundancy strategies, to mitigate engine failure costs; but even that is constrained by catastrophic engine failures that destroy the vehicle, which may be a significant fraction of all failures.

All of these liquid engine attributes (I_{sp} , engine thrust-to-weight, production cost, life, failure rate, and catastrophic failure fraction) are varied from baseline values as a function of three phased technology investment levels. The specific impulse improvements of LOX/LH₂ engines are small because they already achieve near theoretical values of combustion efficiency. LOX/hydrocarbon engines have higher I_{sp} improvements.

Vehicle Sizing

This study fixed payload mass at 12,000 pounds to a polar low earth orbit. For most subsystems, vehicle sizing was done through simple weight estimating relationships. For example, avionics was fixed at 1000 pounds for the booster and 1500 pounds for the orbiter.

Wing, tail, thermal protection system (TPS), and control system weights were scaled to planform-area for each stage. Orbiter TPS weight was 2.5 times heavier per unit area than booster TPS. Fuselage weight was scaled with fuselage surface area. Reaction Control System (RCS) and landing gear weight were scaled to stage dry weight. Tank weights were scaled to tank surface areas, and pressurization was scaled to tank volume; both depended on propellant type.

Planform area, fuselage size, and vehicle dimensions were, in general, a function of propellant volume. A flyback propulsion system was also sized for the booster.^{5,6} It was based on a low bypass turbofan. Booster flyback propellant weight was based on the Breguet range equation.

Engine weights were a function of engine thrust-to-weight, which depended on technology level and propellant type. For this study, the booster and orbiter were assumed to operate serially. Booster thrust was set by a requiring takeoff thrust to equal 1.3 times gross vehicle lift-off weight (GLOW). Orbiter thrust was set equal to 1.1 times orbiter ignition weight.

Residual propellants were accounted for and depended on propellant type, liquid hydrogen being set

at 7%, liquid oxygen at 2%, and storable propellants at only 1%.

Mass properties were evaluated using a spreadsheet and were used to set the input into the Program to Optimize Simulated Trajectories (POST). Acceleration was limited to 3 g's and dynamic pressure was constrained to no more than 1200 pounds per square foot. Staging velocity was optimized for lowest gross weight.

Table II summarizes the weights of the baselines of the five vehicle concepts of Table I. Of the five baseline concepts, the lowest gross weight vehicle was the all LOX/LH₂ vehicle (Concept 4). The LOX/HC booster, LOX/LH₂ orbiter concept (Concept 2) actually had the lowest inert weight. Note that hardware development and production costs are estimated using inert weight, and are a large part of LCC.

| Concept | 1 | 2 | 3 | 4 | 5 |
|---------------|---------|--------------|--------|---------------|-----------|
| Booster Inert | 179000 | 42000 | 92500 | 58700 | 81600 |
| Booster Prop | 1950000 | 570000 | 740000 | 380000 | 1,060,000 |
| Orbiter Inert | 29000 | 30400 | 15800 | 22800 | 23000 |
| Orbiter Prop | 310000 | 160000 | 120000 | 100000 | 200000 |
| Total Inert | 210000 | 72300 | 108000 | 81500 | 104700 |
| Payload | 12000 | 12000 | 12000 | 12000 | 12000 |
| GLOW | 2500000 | 810000 | 980000 | 570000 | 1400000 |

Table II. Baseline concept weights (pounds mass)

Mission Model

The mission model adopted to evaluate LCC stressed a system capable of rapid operations tempo.⁷ It provided for a nominal launch rate of once a week with occasional surges to as many as three launches a day, sustained for several weeks. It averaged out to about a million pounds per year delivered to LEO.

The mission model is used to drive facility requirements, the number of vehicles, and number of operational personnel. All vehicle concepts with all varying technology levels were required to meet the mission model. Vehicle losses were accounted for due to both end of nominal lifetime and unreliability attrition.

Operations Model

In order to project cost, a common concept of operations was developed.⁸ Vehicles are launched vertically from a very clean pad in a "gas-and-go" type operation. No vehicle integration is allowed on the pad. Booster and orbiter are serially burned to optimal staging velocity, with the booster using a jet engine to return at subsonic speeds to the launch site following staging, reentry, and aerodynamic deceleration. The orbiter is also returned to the launch site. Both orbiter and booster are landed horizontally and immediately

taken to a post flight processing facility. There they are made safe and are initially inspected. Servicing is scheduled with the aid of a vehicle health monitoring system. Orbiter and booster are then moved to the large vehicle processing facility, where storage and preliminary vehicle integration are also housed. The vehicle processing facility is envisioned as a shirtsleeve environment. Final vehicle pre-flight preparation, including payload integration, is performed in a separate facility where special safety rules are enforced.

As shown in Figure 2, a single primary operating location is assumed. The baseline vehicle turn time was on the order of three to four days, depending on technology level and propellant type. These were based on extrapolations of advanced complex aircraft rather than the space shuttle.

The booster and the orbiter are both returned to the launch site and are horizontally landed on a runway. The vehicles are towed to a post-flight processing facility where they are made safe, initial

post-flight inspection occurs, health monitoring data diagnosed, and preliminary vehicle maintenance actions are identified and scheduled.

Most stage servicing, maintenance, storage, and flight integration is envisioned as occurring in a large vehicle processing facility. Orbiters and boosters are brought to "service bays" where tires can be replaced, engines pulled, TPS removed and/or replaced. Avionics, power systems, and controls would be accessed, inspected, and serviced. Space for horizontal stage storage and flight vehicle integration is also assumed.

Vehicles are moved out of the vehicle processing facility and brought to a payload integration and pre-flight processing facility. One day is allowed for payloads to be integrated with the vehicle in this limited access facility, with hazardous operations (squib installations, OMS/RCS propellant loading, etc.) performed here. At this point, the vehicle could be launched within a few hours of demand yet stored in this condition for months.

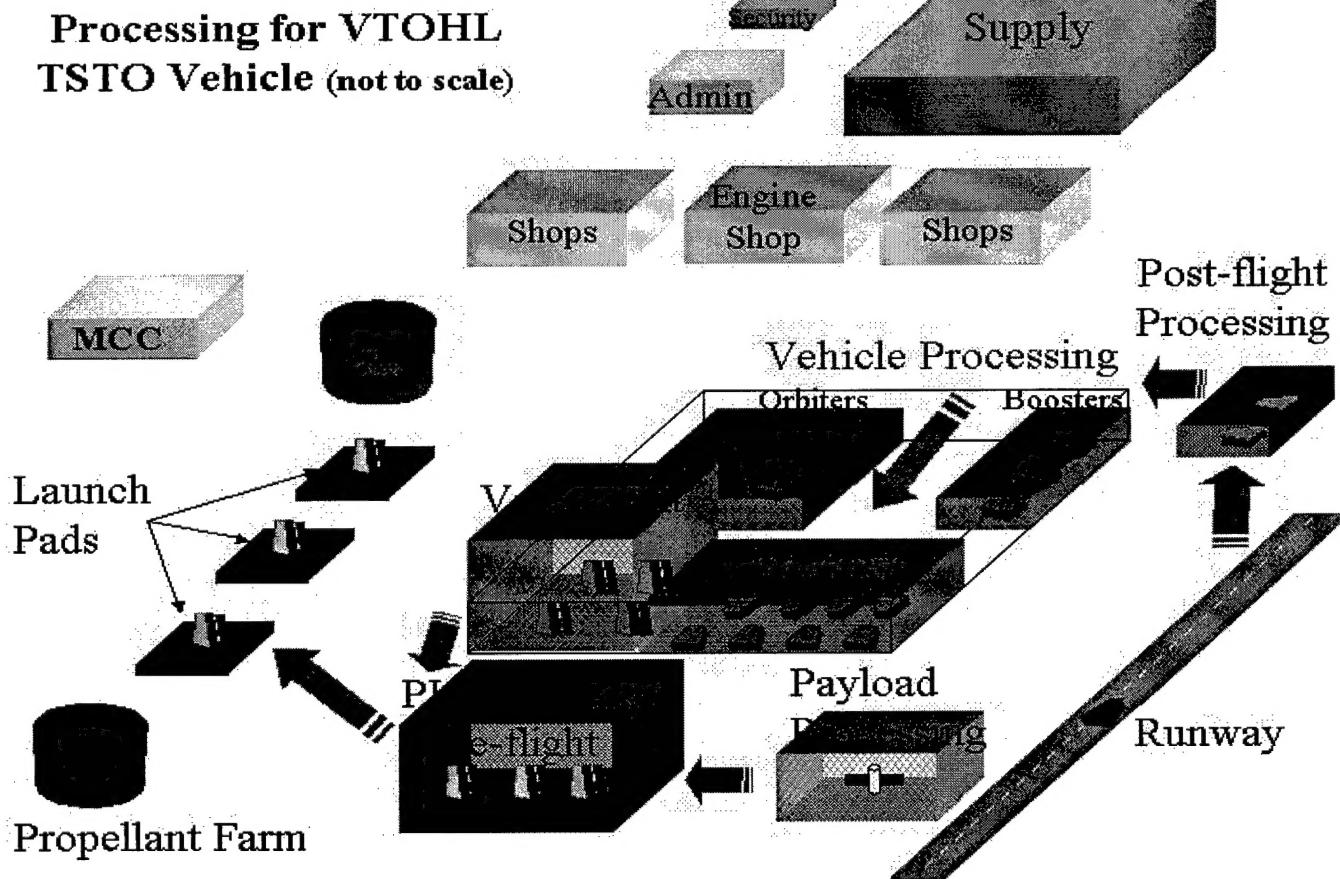


Figure 2. TSTO Vehicle Processing Concept of Operations

The integrated vehicle is rolled to the launch pad, fueled and launched. Cost effective operability is achieved by integrating the vehicle before moving to the launch pad.

A modular mission control center for individual mission planning, control, and oversight is included. A propellant farm adequate to support a hundred missions is included. Shops for servicing and maintaining individual subsystems (e.g., propulsion, avionics, controls, TPS) are modeled. Personnel are also provided for supply, security, and administration. Overall there are about 800 personnel that are assumed to support launch system operations.

Vehicle Reliability

Vehicle reliability issues were approached as failure probabilities.⁹ Reliability was allocated to avionics, airframe, attitude control, TPS, and propulsion for the three vehicle flight segments. The segments were boost phase, orbiter flight after separation, and booster flight after separation. Orbiter and booster separation reliability was included for the boost phase, and flyback propulsion reliability was included for the booster flight after orbiter separation.

Propulsion reliability assumed a probability of failure that was improved with increasing technology investment. Engine *system* reliability was based on an ability to achieve orbit with an arbitrary single engine failure. Orbiters used three engines where two engines could supply 1.1 times the orbiter's separation weight in thrust. Boosters used five engines where four engines could supply thrust equal to 1.3 times the vehicle gross-lift-off-weight (GLOW). A loss of vehicle was assumed if two engines of a stage failed on a given flight. A percentage of all engine failures were assumed to be catastrophic.

Life Cycle Cost (LCC)

Concepts were evaluated with a common LCC estimation methodology. The study goal was to identify propulsion technology investment leverages. Therefore, the fidelity of many non-propulsion subsystem models is crude and contributes to uncertainty in the absolute LCC value. However, the LCC models are uniformly applied to all concept alternatives, and the relative cost differences are significant.

LCC is broken into development cost, facility costs, production and maintenance costs, operations costs, and unreliability costs. In order to estimate the costs, a notional system schedule was developed for uniform concept evaluation. Figure 3 shows the assumed system schedule for a 2010 technology

freeze for system development. A 6-year schedule is assumed to reach an initial operational capability (IOC), and another six years is assumed needed to reach full operational capability (FOC). The system is operated at FOC for 20 years.

R&D end date was based on study technology level. Level I technology is based on a near term technology delivery. Level II is delivered five years later, and level III is provided five years after that.

Development and production costs were estimated for each major subsystem.¹⁰ Subsystems included are fuel and oxidizer tanks, pressurization systems, vehicle and engine structural elements (e.g., intertanks, skirts, engine mounts, thrust structure, gimbals, etc.), flight controls and surfaces, electrical and avionics, wings and tail, landing gear, TPS, and propulsion. Most of these cost estimating relationships (CERs) are weight based, of the form $a*weight^b$, where 'a' and 'b' vary according to subsystem. Engine cost estimating relationships, however, were also dependent on chamber pressure, thrust level, engine cycle selection, and propellant type.

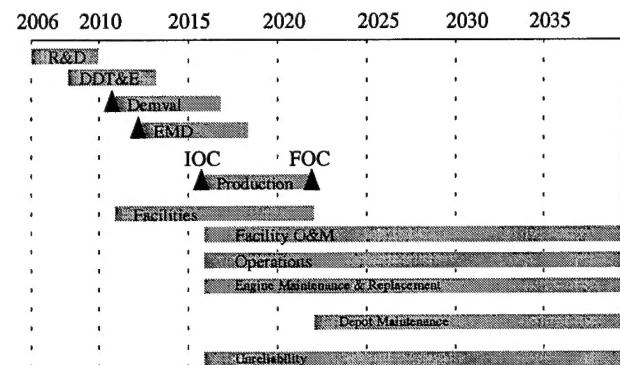


Figure 3. Notional TSTO System Schedule

Ordinary vehicle maintenance is not modeled beyond a simple operations manning requirement. Regular vehicle depot level maintenance is estimated to cost 25% of theoretical first unit cost and is averaged over the entire mission model. Engine maintenance costs were estimated as 30% of their acquisition cost and averaged as a cost per flight. A detail in the study was a criterion that if any engine were shut down abnormally, it would have a depot maintenance performed. Thus the average number of flights per engine maintenance cycle is slightly less than the engine design goal.

Facility costing was generally based on vehicle size and launch rate requirements. The approach was to define nominal facility sizing

characteristics and throughput times. Most facility elements had an acquisition and maintenance cost that was proportional to its size (based on vehicle planform). The launch pads were scaled to vehicle gross weight. Facility elements were duplicated to meet launch operations tempo requirements. Facilities for supply, shops, security and administration were included.

Operations costs were based on a manning profile. Individuals were assigned to each vehicle element (crew chief, load master, propulsion, avionics, controls, power, etc.). Additionally, personnel were assigned to each facility element. Over 800 personnel were required to man the squadron for the assumed mission model.

Unreliability costs accounted for partial losses of vehicle elements. For example, an average 0.6 boosters were lost over 20 years at the highest technology level. This was an unreliability cost of 0.6 times the nominal cost of a booster, spread over the operational life of the system. Unreliability costs also included an additional fixed cost of \$200 million per loss for failure investigation, identification and validation of corrective actions, and fleet-wide fix implementation.

Life cycle costing was performed in constant FY01 dollars.

Sizing Results

A comparison of the gross-lift-off-weight (GLOW) of all five concepts at all technology levels is summarized in Figure 4. It shows a very large reduction in GLOW for all vehicles. Concepts that relied on hydrogen-fueled stages had generally lower GLOW than hydrocarbon-fueled concepts. With level III technology, however, the difference in concept GLOWs was very modest. The all LOX/LH₂ vehicle concept (Concept 4) has the lowest GLOW at all technology levels.

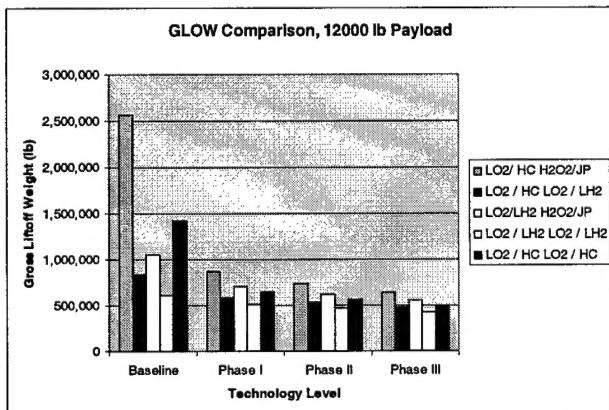


Figure 4. GLOW Comparison

As noted in the baseline results, the GLOW of a concept is dominated by propellant weight, but propellant only accounts for a tiny fraction of vehicle cost. Inert weight tends to give a more accurate picture of cost than gross weight. Figure 5 shows the comparison of the inert weights of the five concepts at all of the technology levels studied.

The results show that although the LOX/HC boost, LOX/LH₂ orbiter concept (Concept 2) has the lowest inert weight at the baseline level of technology, it is the all LOX/HC vehicle (Concept 5) that has the lowest inert weight at all advanced technology levels.

This result leads to the plausibility that lowest life cycle costs are to be found with the all LOX/HC vehicle concept, since that vehicle is inherently more operable without LH₂. It is also physically smaller, and therefore easier to maintain and can use smaller, less costly, facilities.

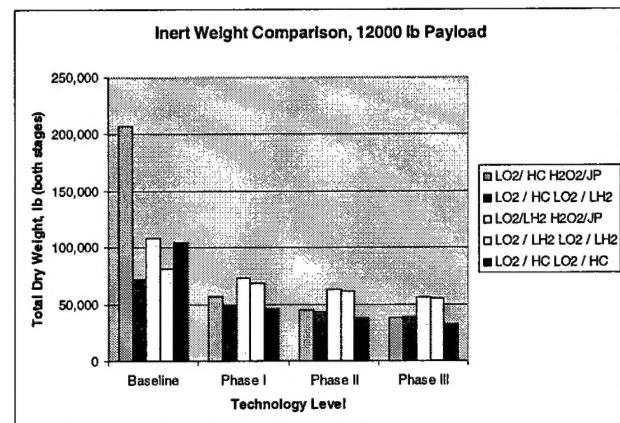


Figure 5. Inert Weight Comparison

Operations Modeling Results

When the vehicle concepts were projected into the operations model with the requirement of meeting the mission model, a total number of boosters, orbiters, and their respective engines were determined, along with the number of facility elements required to meet the mission model.

The number of boosters varied from 13 (baseline, all LOX/LH₂ vehicle concept) to 10 (all LOX/HC vehicle at all advanced technology levels). Similarly, the number of orbiters varied from 16 to 13 for the same cases. More boosters and orbiters were required for LOX/LH₂ cases because of slower operations tempo capability.

The number of engines required showed dramatic variation with technology level, but varied only slightly between vehicle concepts. At baseline technology, 640 to 650 orbiter engines, and 1020 to 1040 booster engines were required to meet the

mission model. With level I technology, the numbers dropped to 140 to 150 orbiter engines, and 210 to 220 booster engines required. Level II required half the engines of level I, and level III dropped the number of engines by another 10 for each stage. The driver for the tremendous drop in engine numbers was the improved number of reuses allowed by the higher technology levels.

Facilities were duplicated as needed to achieve the required operations tempo. The study assumptions led to a requirement for three launch pads, four flight-preparation-and-payload-integration bays, four vehicle assembly bays, six orbiter maintenance bays, three booster maintenance bays, and a single post-flight processing facility with a separated booster and orbiter cell.

Cost Results

Life cycle costs were calculated through a spreadsheet program. Although a cost is reported to the nearest dollar, a number of factors contribute to a very large uncertainty band. The mission model may be incorrectly chosen, the payload size different, the vehicle sizing inaccurate, the CERs off, and other system costs not included. The authors believe the LCC error is about -20% to +100%. However, all of the cases studied are off in the same direction, so the relative values do provide insight into relative LCC relationships between the concepts and related rocket technology improvements.

Figure 6 shows the life cycle cost of the five concepts at all of the technology levels. Every phase of technology investment results in savings of over a billion dollars. The most advanced technology has a life cycle cost that is half of the baseline cases. The all LOX/HC vehicle (Concept 5) does achieve the comparative lowest life cycle cost with any level of technology above baseline.

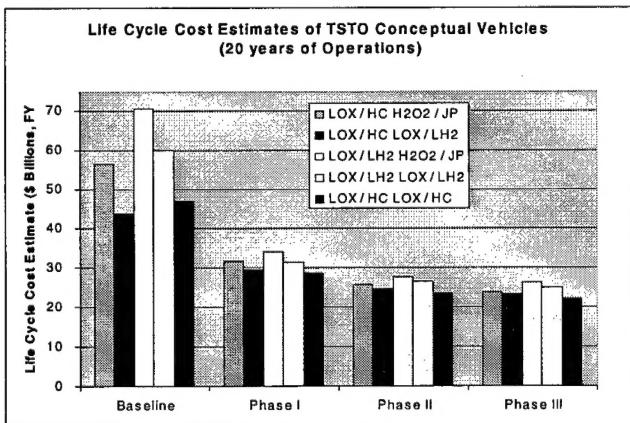


Figure 6. Life Cycle Cost Summary

It is instructive to dig a little deeper into what makes up these costs. In Figure 7, the costs per year are shown by major cost elements for the best baseline concept (LOX/HC booster, LOX/LH₂ orbiter). For comparison, Figure 8 shows the cost per year for the all LOX/HC vehicle with advanced.

Figures 7 and 8 show that substantial operations and production cost savings are achieved through a somewhat higher initial investment. The initial investment cost is higher, and the system is delayed as to when it is made fully operational. Also note that failure costs are also lowered to the point of being trivial.

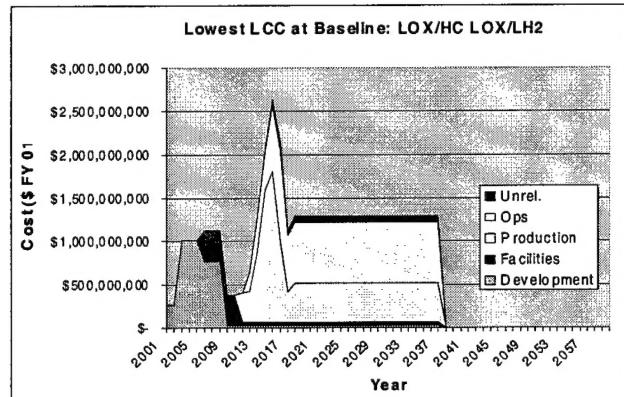


Figure 7. Cost per Year of Best Baseline Vehicle Concept (LOX/HC Booster & LOX/LH₂ Orbiter)

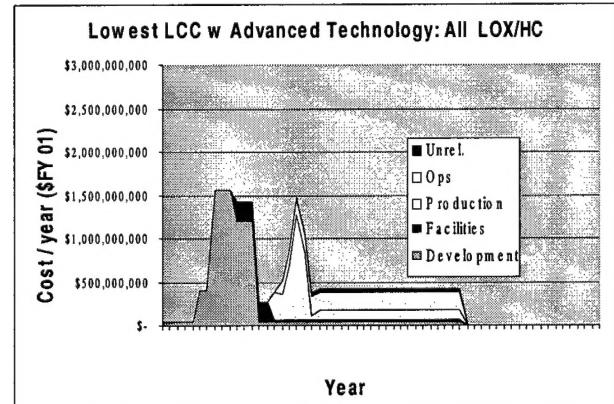
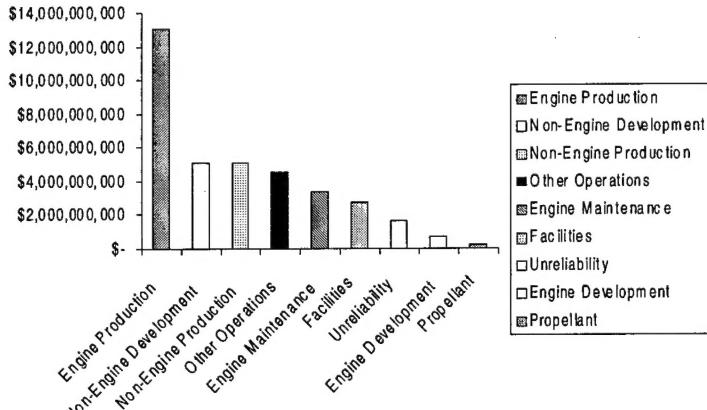


Figure 8. Cost per Year of Best Advanced Technology Vehicle Concept (All LOX/HC Vehicle)

A quick study of Figure 9 reveals that the majority of the cost savings between the cases is found in huge reductions in the engine production cost and the related engine maintenance cost. This is due to the large increase in engine lifetime with improved technology investment. The cost per additional flight is estimated at \$11 million for the best baseline case, which was reduced to \$3.5 million for the all LOX/HC level III technology vehicle.

LOX/HC LOX/LH₂ Baseline Tech Level LCC=\$36,440,000,000

LOX/HC LOX/HC Tech Level 3 LCC=\$18,560,000,000

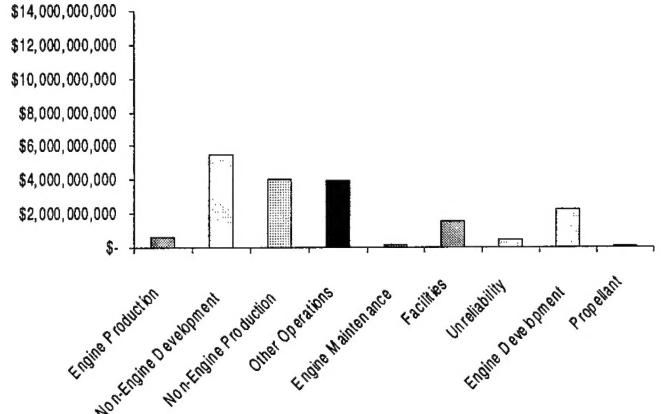


Figure 9. Life Cycle Cost Contributors

Sensitivities

Sensitivities were run to evaluate the importance of assumptions. The first of these was a question concerning how expensive a future hydrocarbon fuel could be before there is no longer a life cycle cost benefit. In the study the nominal hydrocarbon cost was set to a nominal kerosene cost of \$0.25 per pound. The hydrocarbon cost per pound was increased to the point where the all-hydrocarbon vehicle was no longer the lowest life cycle cost. The LCC advantage of the all-hydrocarbon vehicle system was lost once the hydrocarbon fuel cost rose to slightly above \$10 per pound.

The question was asked regarding the relative contribution of the various propulsion technology improvements. Referring back to Figure 9, and considering the tremendous reduction in the number of engines with advanced technology, it is clear how important engine lifetime is to the LCC. However, it is not clear what the relative importance of I_{sp} , engine weight, engine cost, or failure rate improvements are to LCC benefits. In Figure 10 a representation of those relative benefits was established by running individual technology perturbations. The bar on the left is for phase III hydrocarbon engine technology improvements applied to the all LOX/HC vehicle concept (Concept 5). The bar on the right is for level III hydrogen engine technology improvements applied to the all LOX/LH₂ vehicle (Concept 4).

Results show a tremendous payoff for this application for engine lifetime improvements. I_{sp} improvements remain an important goal, but are much less significant than engine life improvements.

Contribution of Different Technology Improvements to Life Cycle Cost Decrease

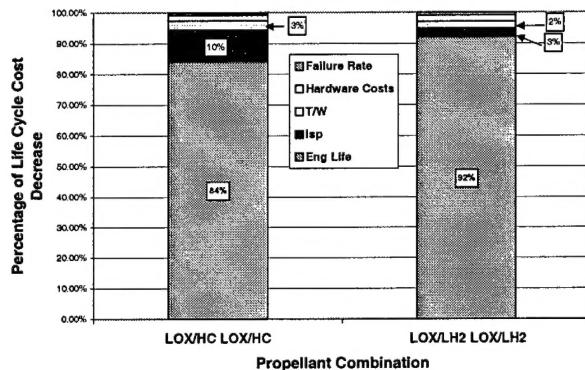


Figure 10. Relative Contribution of Individual Technology Improvements to LCC Savings

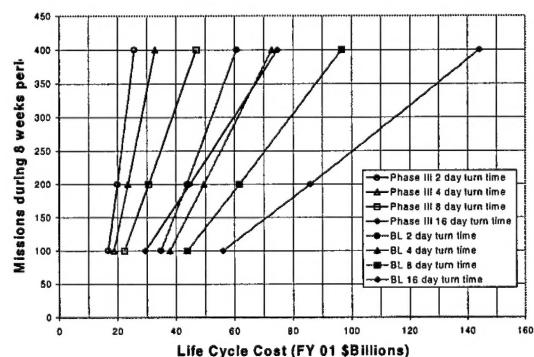
Mission Capability vs. Life Cycle Cost
All LOX/HC systems with varying turn times

Figure 11. Mission Capability vs. LCC

Treating LCC as an independent variable, an evaluation of the mission model sensitivity was performed. Figure 11 asked how much LCC needed to grow for improved mission capability. The analysis scaled the number of missions to generate LCC values. Greater expenditures were required for additional vehicles, engines, and facilities. Total LCC was lower and mission growth less expensive for advanced technology vehicles.

These results are specific to the assumptions made for this study. The results can easily be swayed by many subtle assumptions. For example, Figure 11 shows the life cycle cost variance with varying vehicle turn times also. It shows a cost of billions of dollars for failing to realize fast turn times, and shows that much larger investments are needed to grow the capability.

Mass property and reliability assumptions for non-propulsion subsystems can easily shift the size and sensitivity of the vehicle design. Operability of the overall vehicle processing can be negatively impacted by any subsystem requiring extraordinary servicing for each mission. The trends may remain the same, but exact break points, weights, and costs remain uncertain.

Conclusions

Propulsion technology has a dramatic impact on the LCC of highly operable, fully reusable, two-stage-to-orbit launch vehicles. Advanced propulsion technology can cut LCC in half, and drop recurring costs by a factor of 3. The best vehicle concept studied uses hydrocarbon fuels in both stages, although if an advanced hydrocarbon fuel were to be introduced, it needs to cost below \$10 per pound for this to remain true. It is the improvement in engine reuses that drives most of the savings. Advanced propulsion technology greatly reduces the cost of demanding more mission capability from a nominal system.

Recommendations

This type of study can be an abyss of detail. However, it can be incrementally improved as the community at large inputs their drivers and issues. General methodology improvement is highly desired.

As demonstrations of propulsion technology are defined, LCC analysis aims them to specific thrust levels that could be more easily transferred to specific applications. Leverages of a factor of 2 to LCC require serious investment.

Trades related to payload (a powerful driver of thrust level) and payload support and integration requirements need to be pursued. Both non-recurring

and recurring costs will vary with these considerations and are strongly related to "load factor."

The number of engines also drives thrust level. Using fewer engines is better from both a cost and a reliability perspective, although there is a practical upper bound to engine thrust (~ 2 million pounds force) for cost effective engine development. Issues related to parallel burn versus series burn, with and without propellant cross-feed or engine-out capability, need careful study. Engine-out strategies need to take into account development cost and schedule implications.

Engine reliability goals need to also be tied to the scope and duration of the development program. Study of how engine reliability and life vary with margins in engine weight and I_{sp} need to be done.

The vehicle concepts studied all relied on boosters returning to the launch site under the power of a jet-powered flyback propulsion system. A preliminary initial design was pursued and was found to be a significant booster size driver. More definition and study are required. Trades of flyback propulsion with alternative approaches (e.g., retro firing the booster engines after orbiter staging) should be studied.

The mission selected was very operations tempo driven. Additional study of the implications of short-duration delivery missions versus orbital missions of significant duration is required. There are many subtle operations questions that need study if the vehicle is to be manned.

Other vehicle configurations (e.g., partially reusable systems, air-launched systems, air-breathing booster options, horizontal take-off or vertical landing) should have similar LCC analyses performed to more fully understand their benefits and challenges.

Acknowledgement

LCC systems engineering analysis is a multi-disciplinary activity that cannot be successfully performed without the input of a large number of individuals. We would like to express appreciation for the thoughts and comments of several individuals who contributed more directly to this study, knowing that we cannot fully recognize everyone, and apologize to those unrecognized.

This study could not have been performed if it were not for the initial questions and subsequent encouragement of AFRL's Drew DeGeorge.

We would also like to acknowledge the support of the RMLS study team, and specifically

ASC's John Livingston, AFRL/VA's Greg Moster, and AFFTC's Major Steve Sturmer in the development of our vehicle and operations models. The support and many inputs supplied by CPIA's Mark Coleman have been invaluable in the development of an LCC model.

We would especially like to thank our colleagues at AFRL's Propulsion Directorate at Edwards Air Force Base for the inputs and critique of this effort. Rich LeClaire, Jim Nichols, Alan Sutton,

and Craig Hansen of the Engine Branch provided many helpful inputs. Dr. Ray Moszée, Roy Hilton, and Dr. Tae-Woo Park of our Application and Assessments Branch, and Spiral Technology's Jim Eckmann all had to endure endless discussions of how to model specific aspects of the vehicle and its operations and provided their editorial skills in producing this paper.

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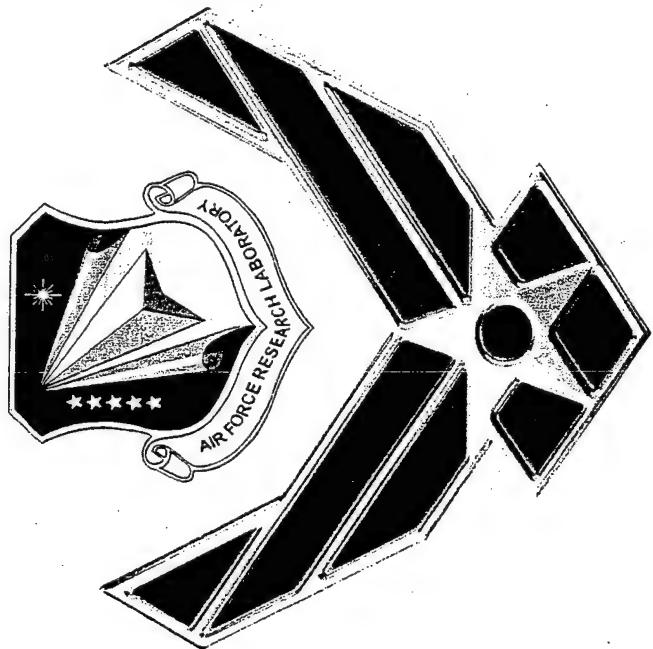
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Rocket Propulsion Technology Impact on TSTO Launch System Cost

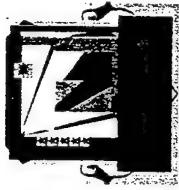
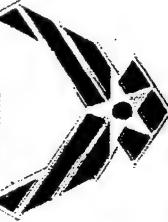
8 May 2001

Jason B. Mossman
Spiral Technology

David R. Perkins
Propulsion Directorate
Air Force Research Laboratory



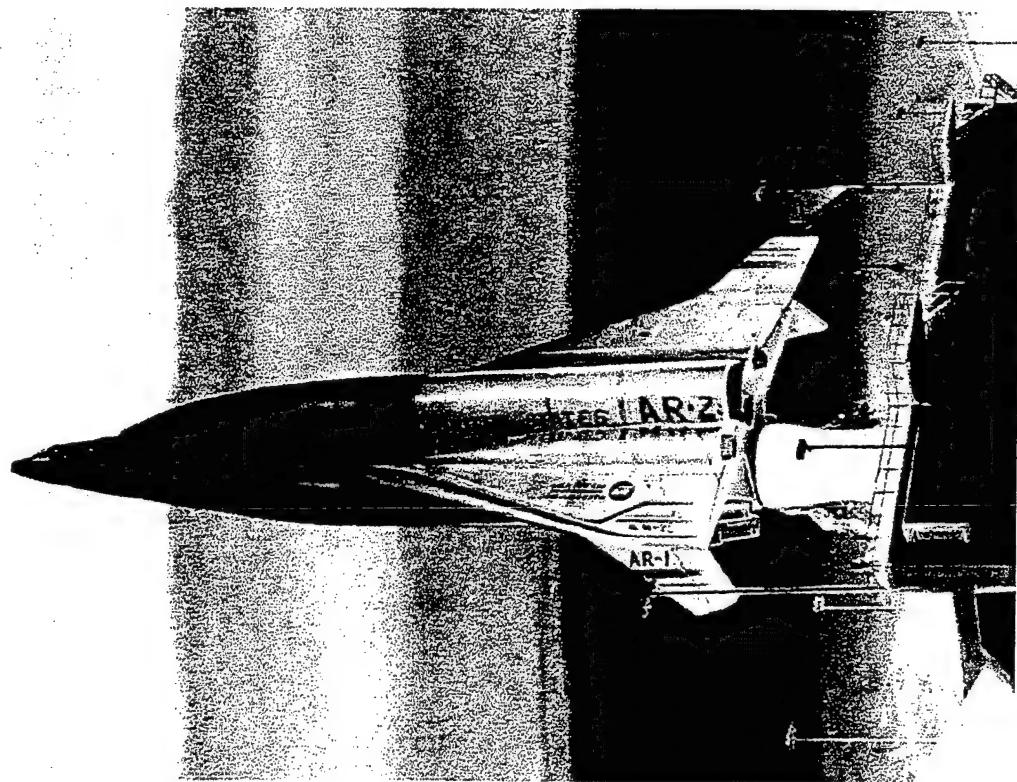
Study Purpose/Approach



- Purpose: Determine LCC benefits of Propulsion Tech

- Approach:

- Fully Reusable TSTO
- Ops-driven mission model
- Ops model for processing
- 5 vehicle concepts
- 4 propulsion tech levels
- Examine sensitivities to assumptions



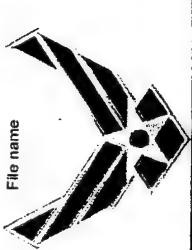


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Why TSTO?

- SSTO appears to be simplest, most operable
- SSTO very demanding (need very efficient engines & extremely light structure)
 - NASP, X-33, X-34, etc. didn't result in SSTOs
 - Significant develop risk for SSTO concepts
 - Very large vehicles
 - Large mission sensitivity
 - Low margins
 - Reliability cost
 - Operability compromises
- TSTO smaller, less sensitive, affords greater margins..Much more feasible

TSTO Study Ground Rules



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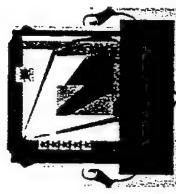
| Concept | Stage 1 | Stage 2 |
|---------|-----------------------|-----------------------------|
| #1 | LOX / HC | H_2O_2 / JP |
| #2 | LOX / HC | LOX / LH ₂ |
| #3 | LOX / LH ₂ | H_2O_2 / JP |
| #4 | LOX / LH ₂ | LOX / LH ₂ |
| #5 | LOX / HC | LOX / HC |

- 1. TSTO, VTOHL winged vehicle
- 2. T/W liftoff=1.3, T/W second stage =1.1 (serial burn)
- 3. Acceleration limited to 3 g's
- 4. Dynamic pressure limited to 1200 psf
- 5. Staged at minimize weight
- 6. 12000 lb_m to polar LEO
- 7. Mass fractions and planform area sized in spreadsheet
- 8. Booster must return to launch site under own power (low bypass turbofan)

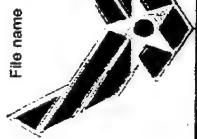
Sizing Approach



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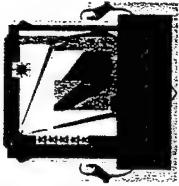


- Used simple weight scaling for most subsystems
 - Models mostly from other studies
 - Subsystems modeled:
 - Structure (Fuselage, wing, thrust structure, etc.)
 - Avionics (a fixed weight)
 - Landing gear
 - Controls, Power, ACS
 - TPS (scaled with vehicle surface area)
 - Flyback propulsion (and fuel)
 - Tanks (residuals also calculated)
 - 3 orbiter engines; 5 booster engines

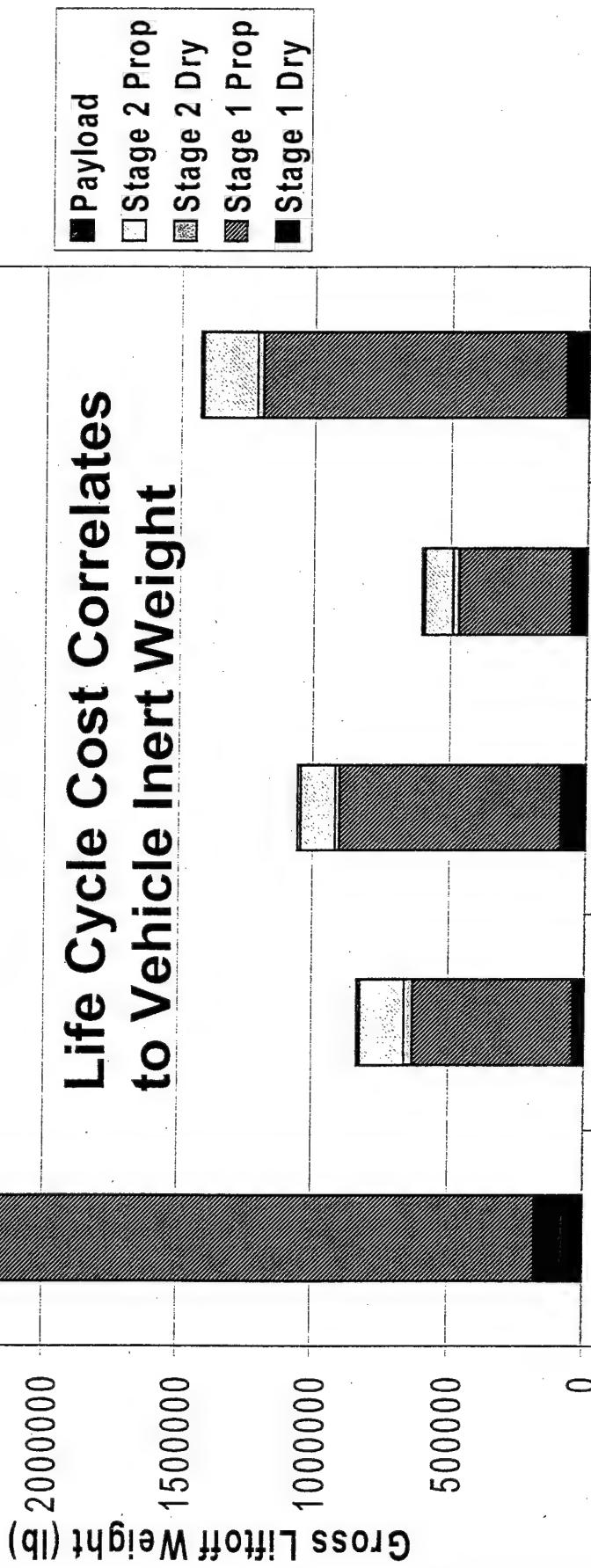


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Baseline Vehicle Configuration



| Concept | Stage 1 | Stage 2 | Payload | GLOW | Inert Wt. |
|---------|-----------|-----------|---------|-----------|-----------|
| #1 | LOX / HC | H2O2 / JP | 12,000 | 2,571,000 | 208,000 |
| #2 | LOX / HC | LOX / LH2 | 12,000 | 835,000 | 72,000 |
| #3 | LOX / LH2 | H2O2 / JP | 12,000 | 1,055,000 | 108,000 |
| #4 | LOX / LH2 | LOX / LH2 | 12,000 | 606,000 | 81,000 |
| #5 | LOX / HC | LOX / HC | 12,000 | 1,427,000 | 105,000 |



Concept #1 Concept #2 Concept #3 Concept #4 Concept #5

Baseline Vehicle Performance



- At Baseline technology level, Concept #2, LOX/HC Booster, LOX/LH₂ Orbiter, has the best performance
 - Lowest inert weight
 - Second lowest Gross Liftoff Weight
 - Lowest staging velocity = minimal flyback & TPS needs
 - Lowest Life Cycle Cost
- LOX/LH₂ for both stages has lowest GLOW, second lowest inert weight, but higher life cycle cost
- LOX/HC for both stages has higher GLOW and inert weights but has relatively low life cycle cost
- Peroxide upper stage concepts do not perform well for this application (highest weights, highest costs)

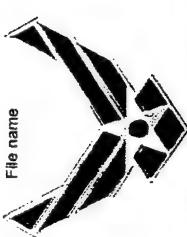


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Rocket Technology and Its Advances



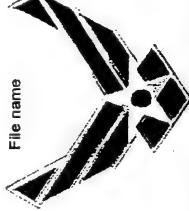
- **Specific Impulse: Thrust per Unit Propellant Flowed**
 - Directly increases ΔV
 - Proportional to $\text{Sqrt}(\text{Temp}/\text{Molecular Wt})$
 - Energetic propellants give higher temps
 - Few things have lower MW than LOX/LH₂ comb
- ΔV also proportional to natural log of initial to final weight (difference is propellant weight)
 - Lower inert weights \Rightarrow more ΔV
 - Higher engine thrust-to-weight desired
- **Wanted: Longer life, more reliable, lower cost engines**



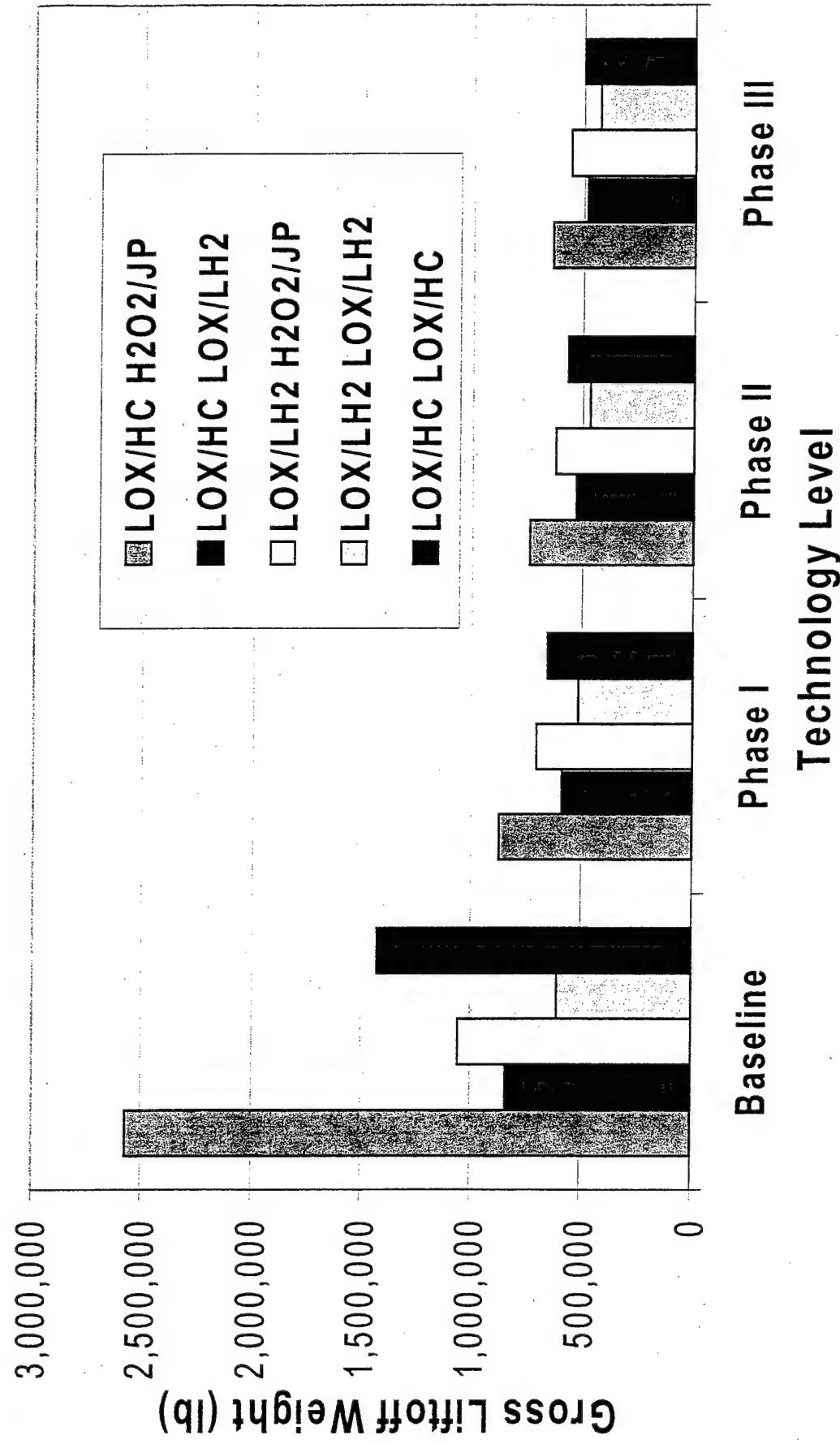
Issues for LH₂ Fueled Propulsion

- LH₂ requires high inert weight
 - Very low density (4 vs. 45 lb/ft³ for kerosene)
 - Tanks are very large
 - Cryogenic storage requires thick insulation
 - Highly compressible liquid
 - High pumping power required
 - Strong variance of density with temperature
 - Much loading uncertainty
 - Results in high propellant residuals
 - 7% vs. 1% for HC
- LOX/LH₂ combustion already very efficient
 - Only small I_{sp} gains possible

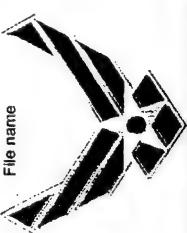
Gross Weights



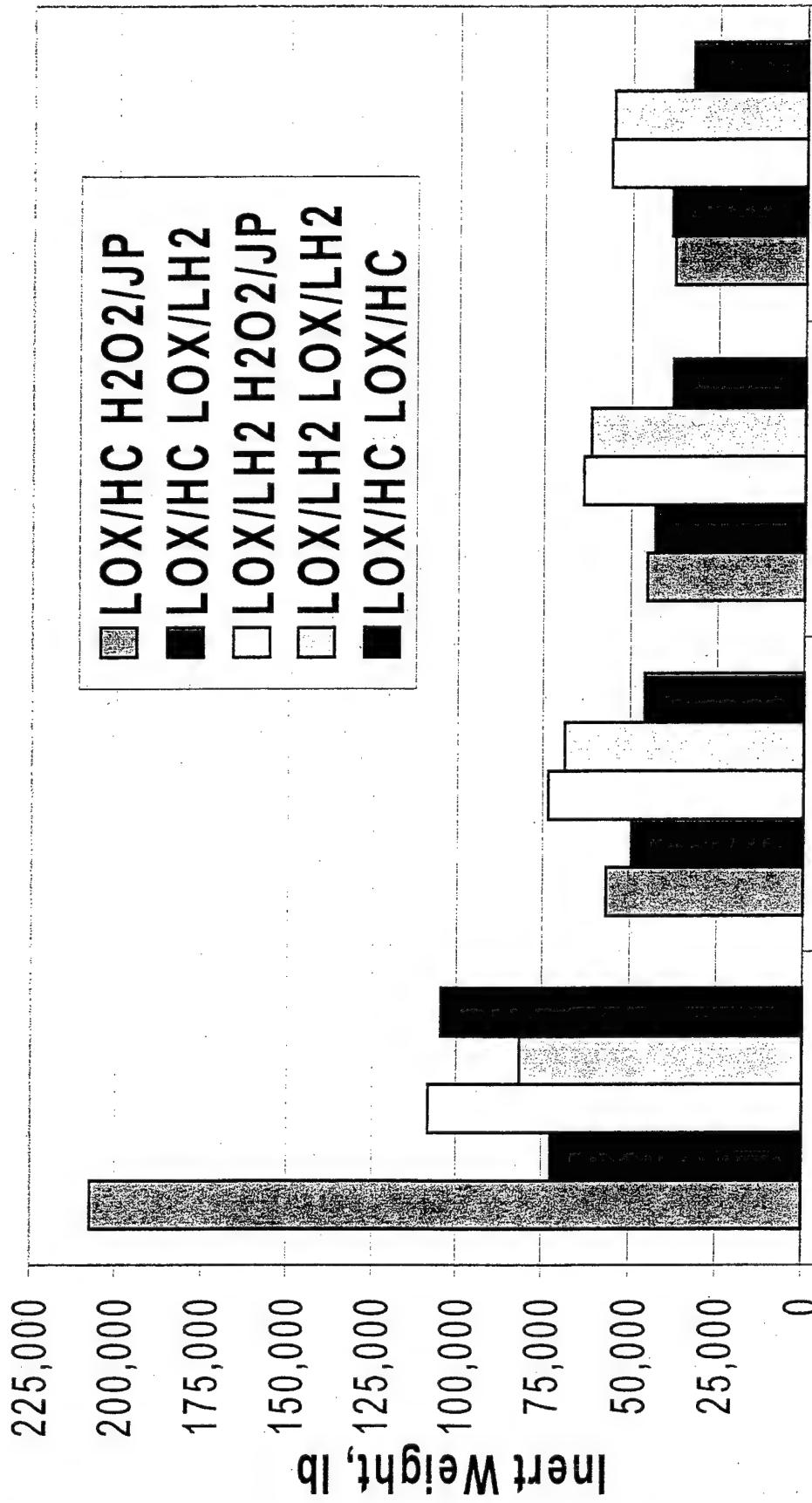
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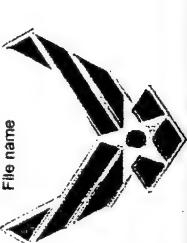
Inert Weights



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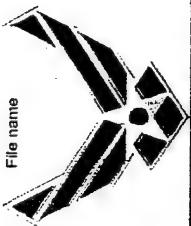


Best TSTO Concept With Advanced Technology



- All LOX/HC looks best with advanced technology
 - Lowest dry weight
 - Lower development & production cost
 - Nearly lowest GLOW
 - Lower propellant cost, smaller launch pad
 - Smallest planform area
 - Smaller, less costly facilities
- Most Likely Lowest Life Cycle Cost

Mission Model & Ops Concept

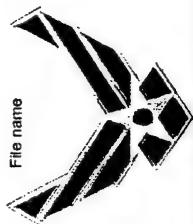


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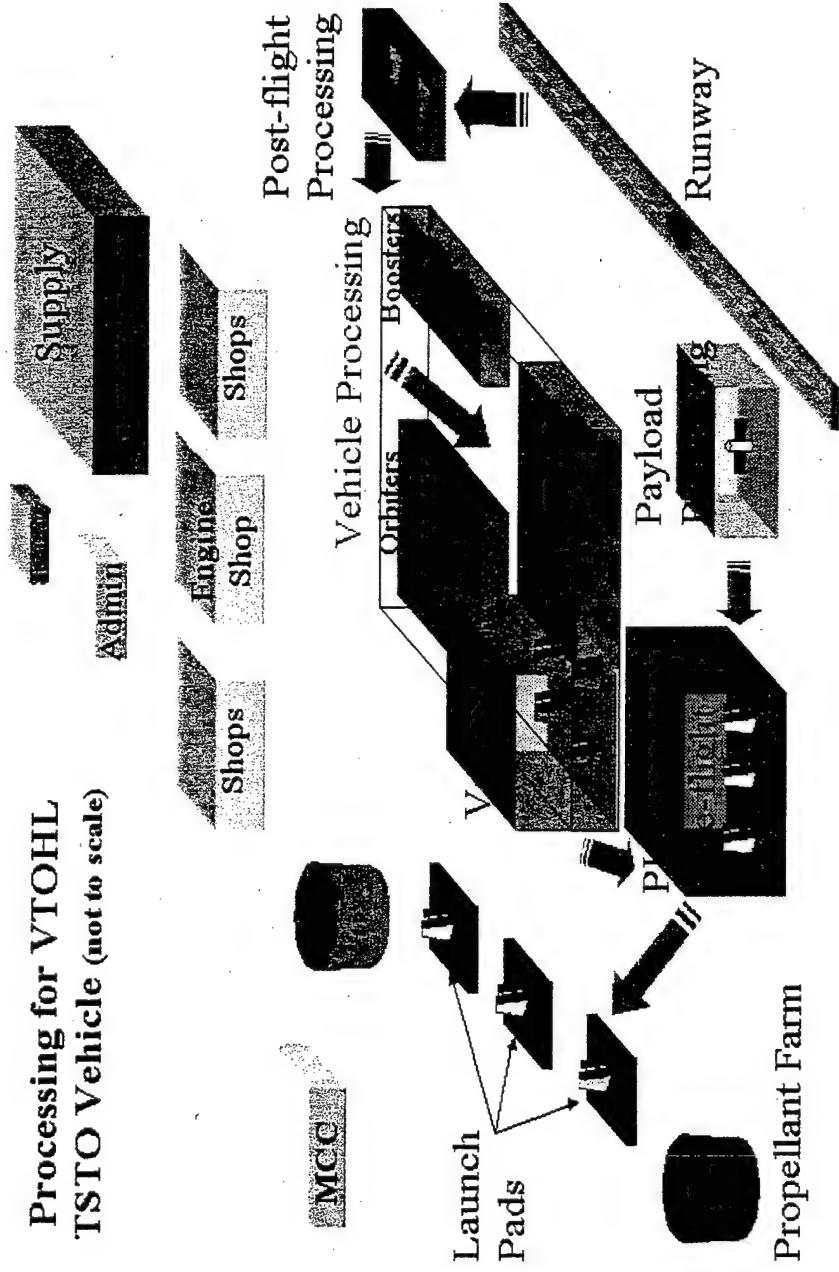
- **Concept must meet demanding mission model**
 - Rapid ops tempo (up to 3 flights / day)
 - Averaged to ~100 missions per year
 - 20 years of full operational capability
- **Adopted aircraft-like ops model**
 - Based on current complex aircraft (e.g. SR-71)
 - Total processing time
 - Orbiter ~4 days
 - Booster ~3 days
 - Assumes ops advances for non-prop subsystems



TSTO Vehicle Processing Concept



Processing for VTOHL
TSTO Vehicle (not to scale)



- Red denotes areas where hazardous chemicals or explosives will be present on the vehicle

Ops Results



File name



- Need ~10 boosters and ~12 orbiters
 - Slight dependence on vehicle type & prop tech level
- Huge baseline requirement for engines
 - Baseline engine life: Only 4 flights
 - ~1000 booster engines, ~600 orbiter engines
- Life improvements drop number of engines by ~10x
- Only 3 launch pads, 4 vertical integration cells needed



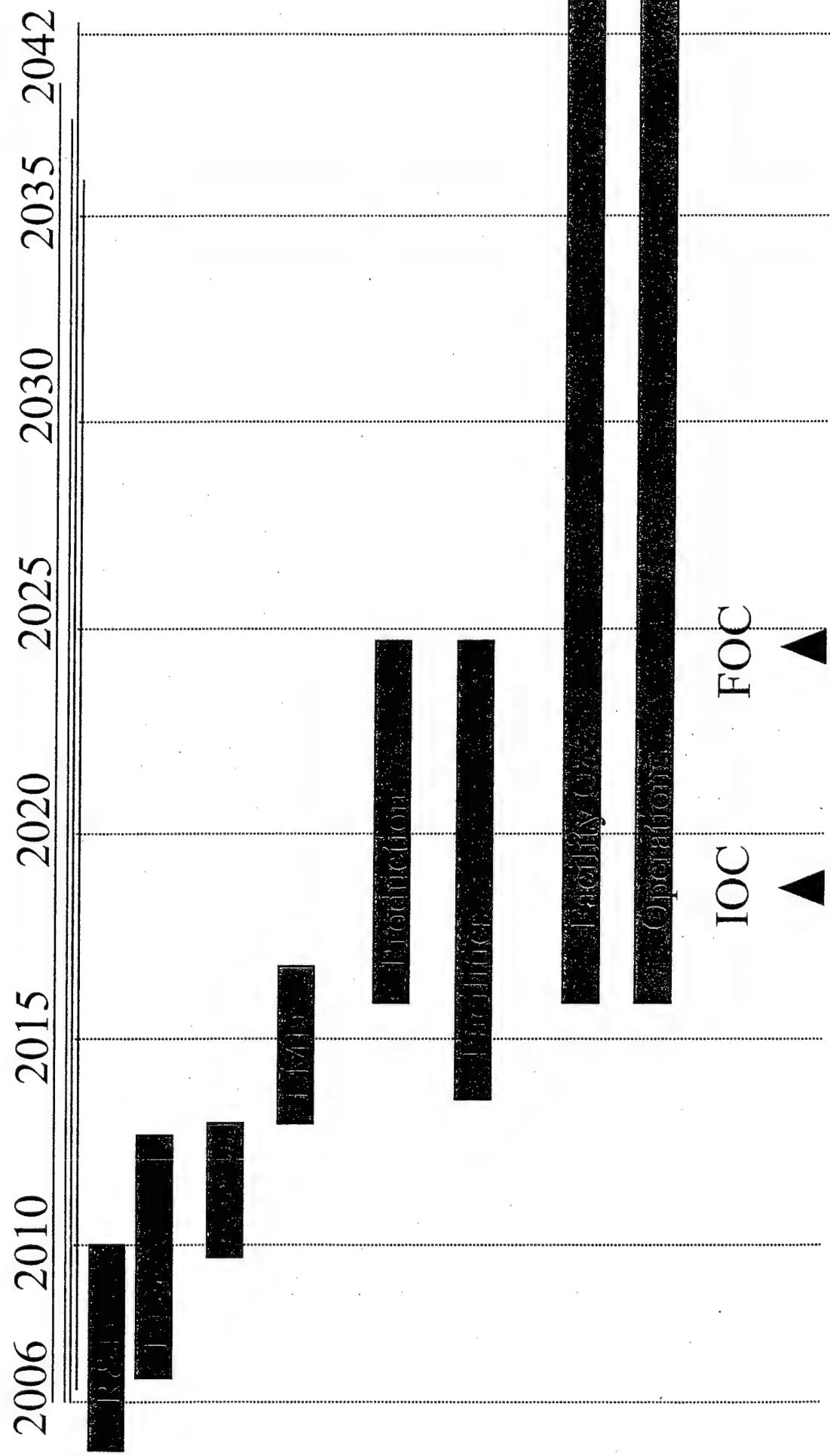
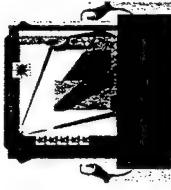
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Life Cycle Costing

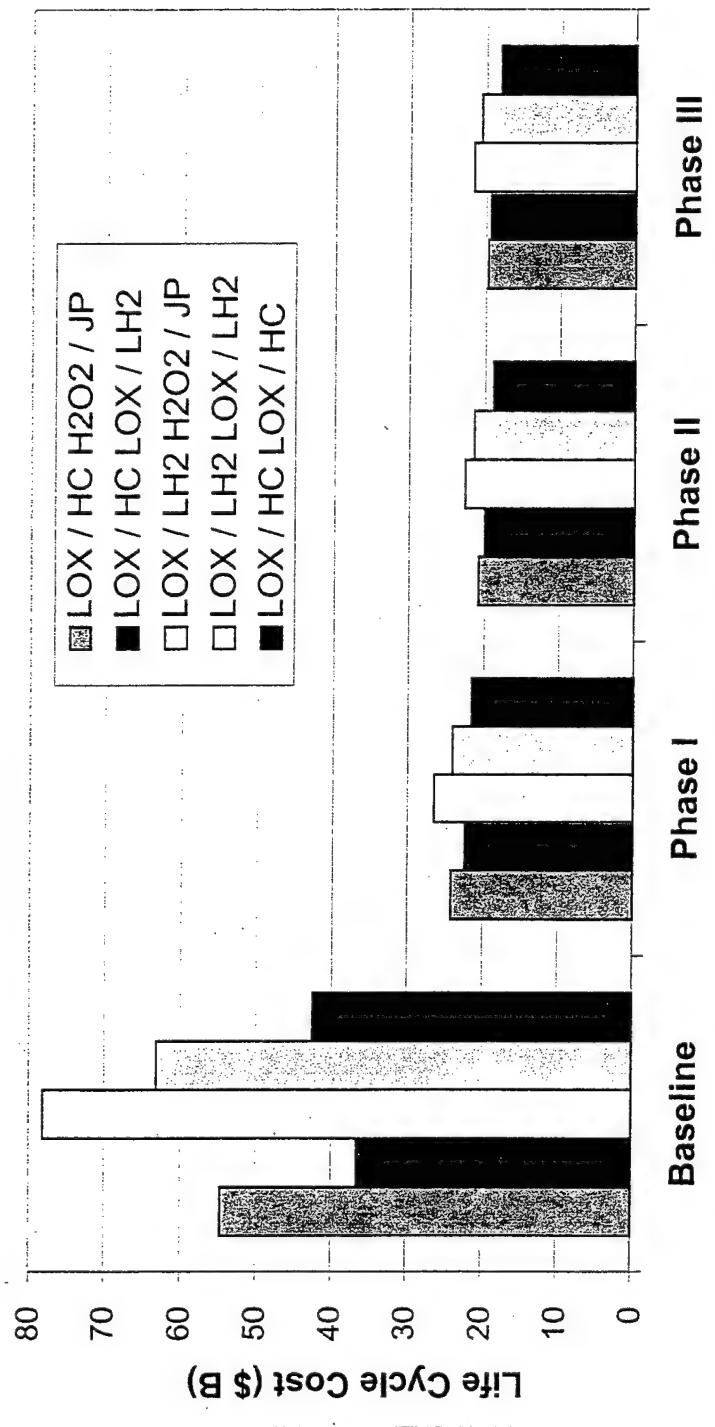
- Includes Development, Facilities, Production, Ops, & Unreliability
- Development & Production cost from weight-based CERs
 - Engine costs also increase with thrust, chamber pressure, complexity
 - Production cost used to scale depot maintenance costs
 - Includes spares
- Facilities generally scaled with vehicle size & ops tempo needs
 - Maintained for system life
- Operations
 - Based on functional manning and fleet size (~ 800 personnel)
- Unreliability includes losses plus \$200M per failure fixed costs
 - Assumed making mission with any single engine loss



National Schedule for Reusable TSTO System



Life Cycle Costs



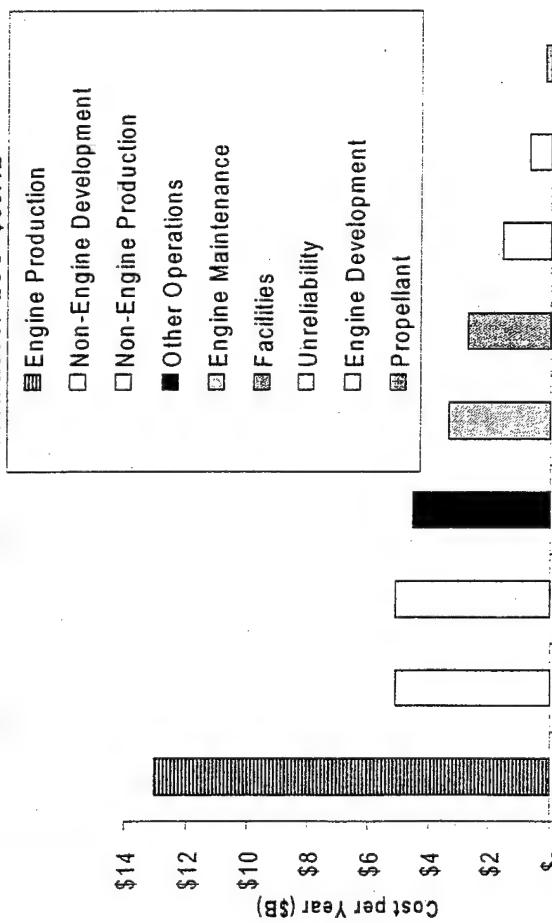
- At baseline, LOX/HC LOX/LH₂ has lowest cost (\$37B ~ \$1600/lb. to LEO)
 - (\$900/lb. recurring cost = \$11M per flight)
- With Phase III tech, All LOX/HC has lowest cost (\$18B ~ \$800/lb.)
 - (\$300/lb. recurring cost = \$3.5M per flight)
- Advanced technology cuts LCC in half, recurring launch costs by 2/3



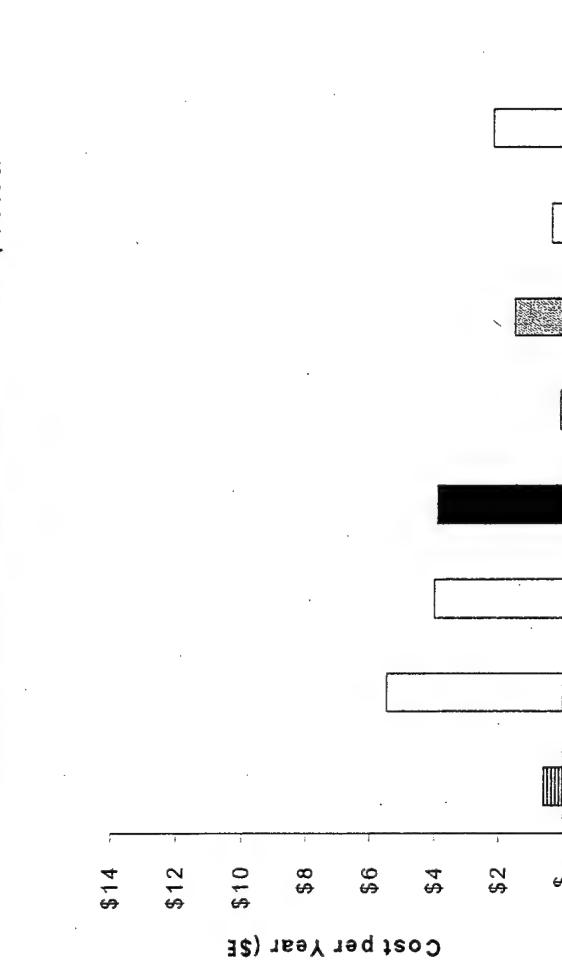


Comparison of Life Cycle Cost for Two TSTO Concepts

LOX/HC LOX/LH₂ Baseline Tech Level LCC=\$36.4B



LOX/HC LOX/HC Tech Level 3 LCC= \$18.5B



- At Baseline, many engines must be produced due to short engine life
- Major expenses:
 - Engine Production
 - Non-Engine RDT&E
 - Non-engine Production
 - Non-engine Operations
 - Engine RDT&E
- With advanced technology, engines are much more reusable, affordable
- Major expenses:
 - Non-engine RDT&E
 - Non-engine Production
 - Non-engine Operations
 - Engine RDT&E



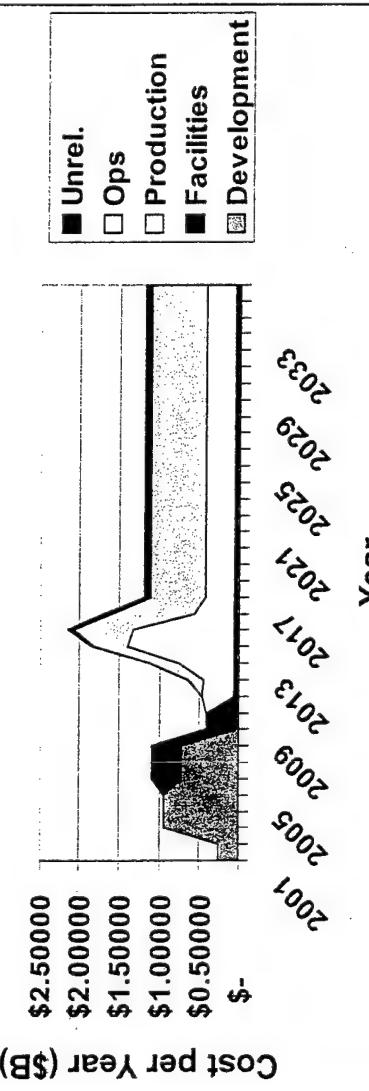
Cost per Year

Best BL vs All HC Advanced Technology



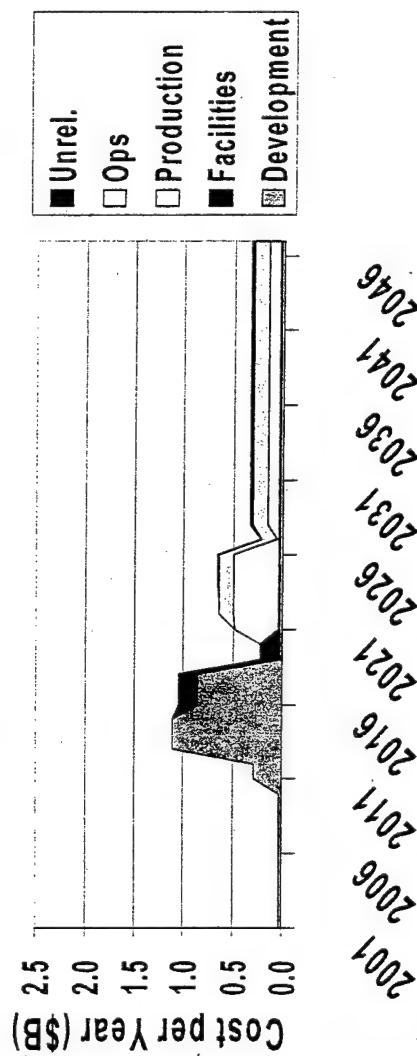
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Best Baseline (H/C Booster, LH2 Orbiter)

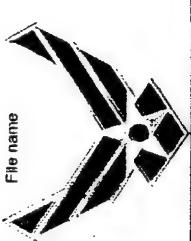


- **Baseline:**
 - Ops & production are major costs

Best w. Adv. Technology (All-H/C)



- **Advanced Technology:**
 - Ops & production are not major costs
 - Development cost is higher than at baseline



File name

LCC Sensitivities

- Propellant Cost

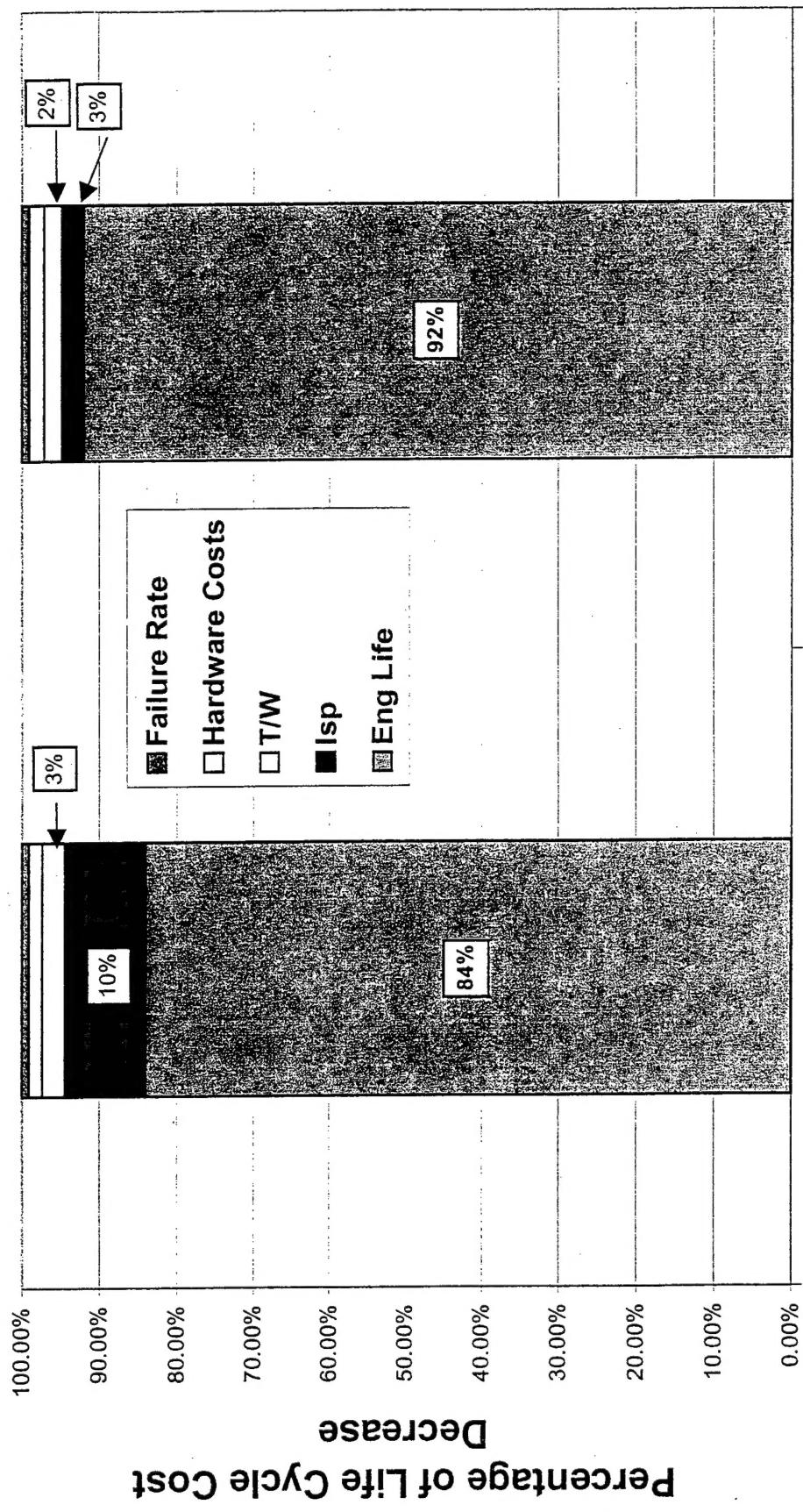
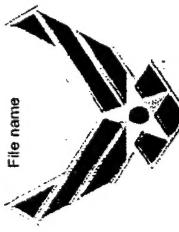
- Advanced HC fuel would have to rise to a cost of over \$10/lb before the all-LOX/LH₂ TSTO vehicle had a lower LCC
 - \$.25/lb was assumed as the nominal cost of HC fuel

- Effect of Performance Related Goals on Life Cycle Cost

- It's the operability improvements that save the most
 - Engine Life is most significant!
 - LOX/HC LOX/HC Phase II
 - 87% of savings from operability goals
 - LOX/LH₂ LOX/LH₂ Phase II
 - 95% of savings from operability goals



Contribution to LCC Decrease of Different Technology Goals



Propellant Combination

LOX/LH2 LOX/HC



File name

Future TSTO Studies

– Hydrocarbon Engine Thrust Level

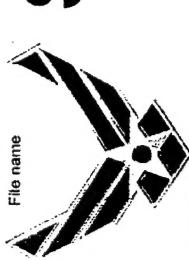
- Payload size and ops tempo variations
- Engine out trade
 - Engine out development vs. better single engine reliability
 - Optimum number of engines on booster and orbiter
- Parallel vs. series burn; Crossfeed; Optimum thrust split
 - Can orbiter and booster engine thrust be similar?
 - What are costs from using a common engine design?

– Refine vehicle and operations models

– Flyback profile optimization

- Flyback altitude, speed, and installed flyback thrust trade
- Type of recovery propulsion

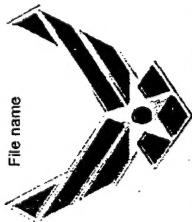
– Other Applications



Summary of Propulsion Technology Payoffs for TSTO Vehicles

- Results valid for operations-driven TSTO vehicles where all non-propulsion subsystems are very operable
- TSTO benefit from propulsion technology:
 - High engine life leads to few engine overhauls and replacements
 - High performance engines lead to lightest dry weight
- Decreased hardware and support costs reduce life cycle cost
- High reliability = few losses and low maintenance costs

Conclusions



File name



- Large cost decreases for a reusable TSTO vehicle with advanced propulsion technology (vs. Baseline)
 - Cut life-cycle-cost in half (~\$20B potential savings)
 - Cut recurring cost by 2/3 (to ~\$300/lb)
- LOX/HC is the lightest and most cost-effective option for TSTO with advanced propulsion technology
 - Illustrates payoffs of advanced HC engine development
- Operability goals (engine life) provide the largest decrease in life cycle cost for an ops driven TSTO